Southwest Fisheries Center Administrative Report H-79-12

Subject to revision

Running head:

The Cost of Information Seeking in the Optimal Management of Random Renewable Resources

Roy Mendelssohn

Southwest Fisheries Center, National Marine Fisheries Service, NOAA
Honolulu, HI 96812 USA

and

Edward J. Sondik
National Heart and Lung Institute, National Institute of Health
Bethesda, MD 20014 USA

Key words:

ABSTRACT

Papers on the management of randomly varying renewable resources have been concerned with uncertainty in the population dynamics. Optimal management regimes in these circumstances depend on the population size, which usually only can be obtained at a large cost. In this paper, algorithms are discussed which allow either for a delay in obtaining the population size, or N years to elapse between population estimates. The algorithms are applied to a model of salmon runs and to an anchovy growth model. In each instance, consistent information delay is found to be costly, while frequent surveys also are found to be costly. These results raise questions as to the traditionally held view on the value of information, and suggest that managers may prefer surveys for reasons other than management policy per se.

Introduction

The treatment of uncertainty when managing fisheries or other renewable resources has been concerned with uncertainty or randomness in the year to year population dynamics (see for example Reed 1974; Walters 1975; Mendelssohn 1976, 1978; Walters and Hilborn 1976; Mendelssohn and Sobel 1979). Policies that maximize the total expected value of a randomly varying population are contingency plans that say if population size x is observed this year, then take harvest action y. Usually, however, observing the population size is costly--either a costly survey is needed to estimate the population size, or else the estimate normally only is available with a delay, but for some cost can be found currently. It appears to be the standard gospel that more information on the status of the population is always good, no matter what the cost expended to obtain the information. In this paper algorithms are discussed which find optimal policies with information delay or surveying costs. The algorithms are applied to a model of anchovy population dynamics (MacCall 1978) and to a model of salmon runs on the Wood River off Bristol Bay (Mathews 1967). The results strongly suggest that in many instances information is very costly--more costly than the gain in expected total value possible from the increased information. Optimal policies are found for no surveying for a period of N years that perform nearly as well as the best policy available with complete information.

Despite the fact that our results suggest that over a broad range of surveying intervals little value is added to management from more frequent surveys, experienced managers still seem to deem surveys as important. We suggest several possible reasons for this discrepancy. Firstly, our intuition in dealing with random situations usually is not that sharp, and it is human nature to always want a little more information, just to be sure. In this case, despite their experience, managers may be overevaluating the worth of the information they receive.

A more likely explanation is that managers are uncertain about the validity of the population dynamics model. In this instance, frequent surveys provide additional information about the true form of the population dynamics, as well as a final measure of safety if our management has failed, partly because we do not understand well even the probabilistic dynamics of the population.

In either case, our results suggest a need for a closer examination of why and how we collect the data we do, and also our attitude towards risk in using this information.

The Models

The anchovy model is described completely in MacCall (1978). Unlike in that paper, we use fishing mortality, not expected catch, as the decision variable, and restrict effort to lie between 0 and 0.2. Fishing mortality of 0.2 produces expected catches over all population sizes slightly greater than the distribution of catches over the last several years. The population dynamics are:

x_t = Biomass in year t ($\times 10^6$)

F_t = Fishing mortality in year t

d = Normal random variable, zero mean, variance = 0.2294

c_t = Catch in year t, a random variable

v_t = Value of catch in year t

lower case alpha α = Discount factor = 0.97

then:

$$x_{t+1} = x_t e^{-(F_t+0.8)} + \left(e^d\left(\frac{1}{3.659} + \left(\frac{1}{x_t} - \frac{1}{3.649}\right)0.695\right)^{-1} - x_t e^{-0.8}\right)e^{-0.152F_t} \tag{2.1}$$

catch in period t is:

$$c_t = \frac{F_t}{F_t+0.8}\, x_t\left(1 - e^{-(F_t+0.8)}\right) + 0.647\left(e^d\left(\frac{3.649x_t}{0.190+0.305x_t}\right) - x_t e^{-0.8}\right) \cdot \left(\frac{0.76F_t}{0.76F_t+0.8}\left(1 - e^{-(0.152F_t+0.16)}\right)\right) \tag{2.2}$$

and the value of the catch c_t is (Huppert et al. 1972):

$$v(c_t, x_t) = (59.67 \times c_t) - (1.8953 \times 10^{-5} \times c_t^2) - (10{,}315 \times c_t \times x_t^{-0.4})\ . \tag{2.3}$$

The goal is to:

$$\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} v(c_t, x_t)$$

$$\text{s.t. } 0 \le F_t \le 0.2 \tag{2.4}$$

The population dynamics for the salmon model are (Mathews 1967):

x_t = Number of recruits in year t

z_t = Number harvested in year t

$y_t = x_t - z_t$ = Number of spawners in period t

d = Normal random variable, zero mean, variance = 0.2098

α = Discount factor = 0.97

Then:

$$x_{t+1} = (e^d)\ (4.077y_t)\exp\left\{-0.800y_t\right\} \tag{2.5}$$

and it is desired to:

$$\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1}(x_t - y_t)$$

$$\text{s.t.} \quad 0 \leq y_t \leq x_t. \tag{2.6}$$

Since fishing mortality is a rate, and can be defined independently of the population size, the anchovy model is sensible as defined in (2.1) -(2.4) even when the present population size is not known with certainty. The same is not true for the salmon model, since if by chance $z_t > x_t$, the statement "harvest z_t" has no meaning. In what follows, it is assumed that z_t is a catch quota each year, and that the actual catch is minimum (x_t, z_t). Then substitute $x_t - \min(x_t, z_t)$ for y_t in (2.5), and the model is sensible for situations where the number of recruits are not known with certainty.

That the actual catch allows for possible depletion of the stock is somewhat unrealistic. Even with a large quota during years of low population sizes, it would be expected that catch per unit effort would decrease enough to insure that the stock would not be completely depleted. However, two justifications are possible for this assumption. Firstly the absorbing state zero can be considered not as absolute zero, but rather as all population levels such that fishing would be impractical for many years. Secondly, we have no basis for setting up the probabilities of the actual catch given the quota and present population size, and the nature of our results suggest that on the whole this assumption has not significantly affected the results of the analysis.

Algorithms and Results

The two algorithms used are based on the work of Sondik (1971, 1978) on partially observed Markov decision problems. The key is to use what information we do know about the population to redefine our state in such a way that transition probabilities for the transformed states can be defined. When there is information delay, what is known is the population size last year and the action taken last year. This is known every period, and with some fiddling (2.1) or (2.5) can be redefined for this definition of a state. Details of this specialization of Sondik's algorithm can be found in Brooks and Leondes (1972).

When we go N years without a survey (N = 0 implies survey every year, the completely observed problem), sufficient information is contained in a probability distribution, the probability of any given population size this period. This also can be readily computed from (2.1) and (2.5). See Sondik and Mendelssohn (1979) for details of the algorithm.

When N > 0, it is necessary to provide an N + 1 year contingency plan, that says if x is the population size at the last survey, then for the next N + 1 years (including the survey year) take the specified harvest action.

f_0 sub zero

Let f(i) be the optimal expected value when starting with population size i in the completely observed model. Let $f_0(i)$ be the optimal expected value in the surveying year, when we will go N years without a survey, and population size i is the estimated population size. And finally, let f(i, a) be the expected value for the transformed state with information delay.

For computational purposes, each model was discretized. The anchovy model was discretized on a grid of 25 population sizes and 26 fishing mortalities (including zero), while the salmon model was discretized on a grid of 26 population sizes (including zero) and 26 possible quotas.

Fig. 1

Figures 1(a)-(c) give an optimal policy for the anchovy model with N = 0, 1, 2, 3. The lines are linear interpolations between the calculated policies at the grid points. The figures compare policies based on how many years have elapsed since a survey was performed.

Fig. 2

Figure 2 shows an optimal policy (with linear interpolation) for the anchovy model with time delay.

Fig. 3

Figure 3 shows the four optimal quotas for the salmon model when we go 3 years without a survey (N = 3), and compares it with the optimal policy for the completely observed problem. An optimal policy for the salmon model with information delays is not easily graphed, but never allows a quota greater than 0.84.

As a measure of the cost of the information, we use two measures throughout, though there are other measures which are both reasonable and possible. The cost of going N years without a survey, compared to going $n < N$ years without a survey is defined as:

sub zero

$$\text{DIFF} = \text{maximum} \left\{ f_0^n(i) - f_0^N(i) \right\} \tag{3.1}$$

The cost of the information lag, compared to no information lag, can be measured by:

$$\text{CDIFF} = \underset{i}{\text{maximum}} \left\{ f(i) - \underset{\binom{\text{harvest}}{\text{action}}}{\text{minimum}} f(i, a) \right\} \tag{3.2}$$

Table 1
Table 2

These values are tabulated in Table 1 for the anchovy model and in Table 2 for the salmon model.

Discussion

To determine the overall value of surveying or not, it is necessary, to include the costs due to surveying or making a current rather than delayed population estimate. Suppose a survey costs c dollars a year, and the cost of no delay is D dollars a year. Then for a discount factor α, the total cost over an infinite horizon of surveying every year is $C/1-\alpha$, and the total cost over an infinite horizon for current population estimates is $D/1-\alpha$. In practice, C or D may be difficult to determine, since, for example, the survey that obtains population estimates for management may also provide better estimates of the transition functions and other valuable scientific information.

However, suppose we always go 1 year without a survey. Then the total surveying cost is $C/1-\alpha^2$, and the savings is $\alpha C/(1-\alpha^2)$. Therefore, surveying every is preferable only if:

$$[1 - \alpha^2/\alpha] \cdot \text{DIFF} > C \tag{3.3}$$

The equivalent formula for 2 years without a survey is:

$$[(1 - \alpha^3/\alpha(1 + \alpha)] \cdot \text{DIFF} > C \tag{3.4}$$

and for 3 years without a survey:

$$[(1 - \alpha^4/\alpha(1 + \alpha + \alpha^2)] \cdot \text{DIFF} > C \tag{3.5}$$

Similarly, current population estimates are desirable only if:

$$(1 - \alpha) \cdot \text{CDIFF} > D \tag{3.6}$$

Both DIFF and CDIFF in (3.3)-(3.6) can be determined independently of C or D. Given this value, and the value of α, the decisionmaker can decide whether more information is worth the cost.

As examples, for the anchovy model, (3.3)-(3.5) become for $\alpha = 0.97$:

$$(0.0609) \cdot (0.0) > C$$

$$(0.0457) \cdot (0.50482) > C$$

$$(0.0406) \cdot (0.7501) > C$$

The cost of a survey would have to be vanishingly small to make it preferable to survey every year compared to surveying every other year, 2 years without surveying is preferred to surveying every year as long as the cost of a survey is greater than \$23,070, and 3 years without a survey is preferable to surveying every year if the cost of the survey is greater than \$30,454. Two years without a survey is preferred to 1 year without a survey if the survey cost is greater than \$30,744, and 3 years is preferred if the survey cost is greater than \$34,280.

Paying for timely information is preferable only if this costs less than \$219,548 per year.

Similarly for the salmon model, surveying every year is preferable only if the cost of the survey is less than the value of a total discounted harvest of 7,260 salmon while current population estimates are worthwhile if the costs are less than the value of a total discounted harvest of 787,020.

Based on these results, it would appear that frequent surveys are costly, while a constant delay in information is expensive. These results can be explained more fully by carefully examining both the models and the optimal policies. For the anchovy model, note that the transistion (2.1) is composed of a deterministic exponential mortality on standing biomass, and a random term on recruitment, which depends only on the biomass at the beginning of the period before harvesting has started. Within a year, the discounted biomass of one unit of standing biomass with no fishing mortality and independent of recruitment, is 0.4358. After 2 years, its discounted biomass is 0.19. This suggests that the problem is really a 2-, perhaps a 3-year problem. This observation is born out by noticing that for N = 2 and N = 3, the same policies are optimal at 0, 1, and 2 years after the survey.

Moreover, the completely observed optimal policy (N = 0) has broad ranges of population sizes over which an optimal policy is the same. If we do not survey next year, we do not know the population size, but with very high probability we do know the policy that would have been chosen if a survey had been taken. If the initial population size is 0.100 and we follow an optimal policy for N = 0, then with a 99.9% chance we would have a population size less than 0.700 next year. In the zone 0.100-0.700, an optimal policy for N = 0 has only one value, that is $F_t = 0$.

If the initial population size was 2.00 and an optimal policy for N = 0 were followed, then with a 95.2% chance the population size next year would be greater than 0.900. The zone 0.900-3.649 has only one value for an optimal policy, $F_t = 0.2$.

The salmon model exhibits similar behavior but for different reasons. Here, there is significant reason for being concerned about a much too high quota when no surveying is being performed. The optimal policy for $N = 0$ has a mean catch of 1,135,700 and a median catch of 980,000 (see Mendelssohn 1978). The optimal policy for $N = 3$ achieves a balance by allowing an increased quota when the population size is known (increased by 560,000 over most population sizes) and a sharply decreased quota during the non-survey years, to lower the risk of overfishing. However, this reduced quota is only 575,700 less than the mean per period catch, and only 420,000 less than the median catch. This balance of an increased catch the year of the survey, and a reduced discounted catch during other years eliminates the relatively rare very large catch during the non-survey years. Therefore, going 3 years without surveying can produce almost as large an expected total value as surveying every year, but at a reduced cost.

The salmon model illustrates much more clearly than the anchovy model why consistent information delays are costly. The key feature in going N years without surveying is that at set intervals of time we find anew the correct population size. This allows for the management to self-correct. With the information delay, we never know the true population size. In the salmon model, we are always running the risk that z_t is very close to x_t. Since absorption into very low population sizes is possible, an optimal policy is weighted heavily by this fact. In fact, it is similar to an optimal policy for the non-surveying years when $N = 3$, but does not have the balancing effect of an increased catch when a survey is made.

Summary

We have demonstrated that it is possible to include the cost of obtaining information into a stochastic management model of a renewable resource. Numerical results suggest that given an accurate transition function for the population, the gathering of costly information cannot be justified by the gains in the total value of the resource. This remark can be tempered by observing that the information gathered for one purpose often has several other uses, so that the true cost of obtaining the information may be difficult to determine.

The technique we propose allows the gain in value from obtaining the information to be calculated independently of the cost of obtaining the information. Simple formulas are then constructed which say to the decisionmaker that the information is too costly if it costs more than a specified amount. This allows the decisionmaker to use both subjective and objective information to determine the worth of the increase in information.

Brooks, D. M., and C. T. Leondes. 1972. Markov decision processes with state-information lag. Oper. Res. 20: 904-907.

Huppert, D, H. Frey, A. MacCall, G. Stauffer, and O. Mathisen. 1972. Anchovy Fishery Management Plan - First Draft. Pacific Fishery Management Council, Portland, Oregon, 170 p.

MacCall, A. 1978. Population models for the northern anchovy (Engraulis mordax). Paper presented at the Symposium on the Biological Basis of Pelagic Fish Stocks (ICES).

Mathews, S. B. 1967. The economic consequencies of forecasting sockeye salmon runs to Bristol Bay, Alaska: A computer simulation study of the potential benefits to a salmon canning industry from accurate forecasts of the runs. Ph.D Dissertation, Univ. Washington, Seattle.

Mendelssohn, R. 1976. Harvesting with smoothing costs. Southwest Fisheries Center Administrative Report 9H, 26 p., National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Honolulu, HI. Submitted for publication.

Mendelssohn, R. 1978. Using Markov decision models and related techniques for purposes other than simple optimization I: Analyzing the consequences of policy alternatives on the management of salmon runs. Southwest Fisheries Center Administrative Report 27H, 23 p., National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Honolulu, HI. Submitted for publication.

Mendelssohn, R., and M. J. Sobel. 1979. Capital accumulation and the optimization of renewable resource models. MS-79-9, College of Industrial Management, Georgia Institute of Technology, Atlanta, GA 26 p. Submitted for publication.

Reed, W. J. 1974. A stochastic model for the economic management of a renewable animal resource. Math. Biosci. 22: 313-337.

Sondik, E. J. 1971. The optimal control of partially observable Markov processes. Ph.D. Thesis, Dept. of Electrical Engineering, Stanford Univ., Stanford, CA, May 1971.

Sondik, E. J. 1978. The optimal control of partially observable Markov processes over the infinite horizon: Discounted costs. Oper. Res. 26(2): 282-304.

Sondik, E. J., and R. Mendelssohn. 1979. Information seeking in Markov decision processes. Southwest Fisheries Center Administrative Report H-79- , p., National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Honolulu, HI.

Walters, C. J. 1975. Optimal harvesting strategies for salmon in relation to environmental variability and uncertainty about production parameters. J. Fish. Res. Board Can. 32: 1777-1784.

Walters, C. J., and R. Hilborn. 1976. Adaptive control of fishing systems. J. Fish. Res. Board Can. 33: 145-159.

Table 1. Maximum loss of total expected economic value in anchovy model from not decreasing survey interval ($\times 10^6$).

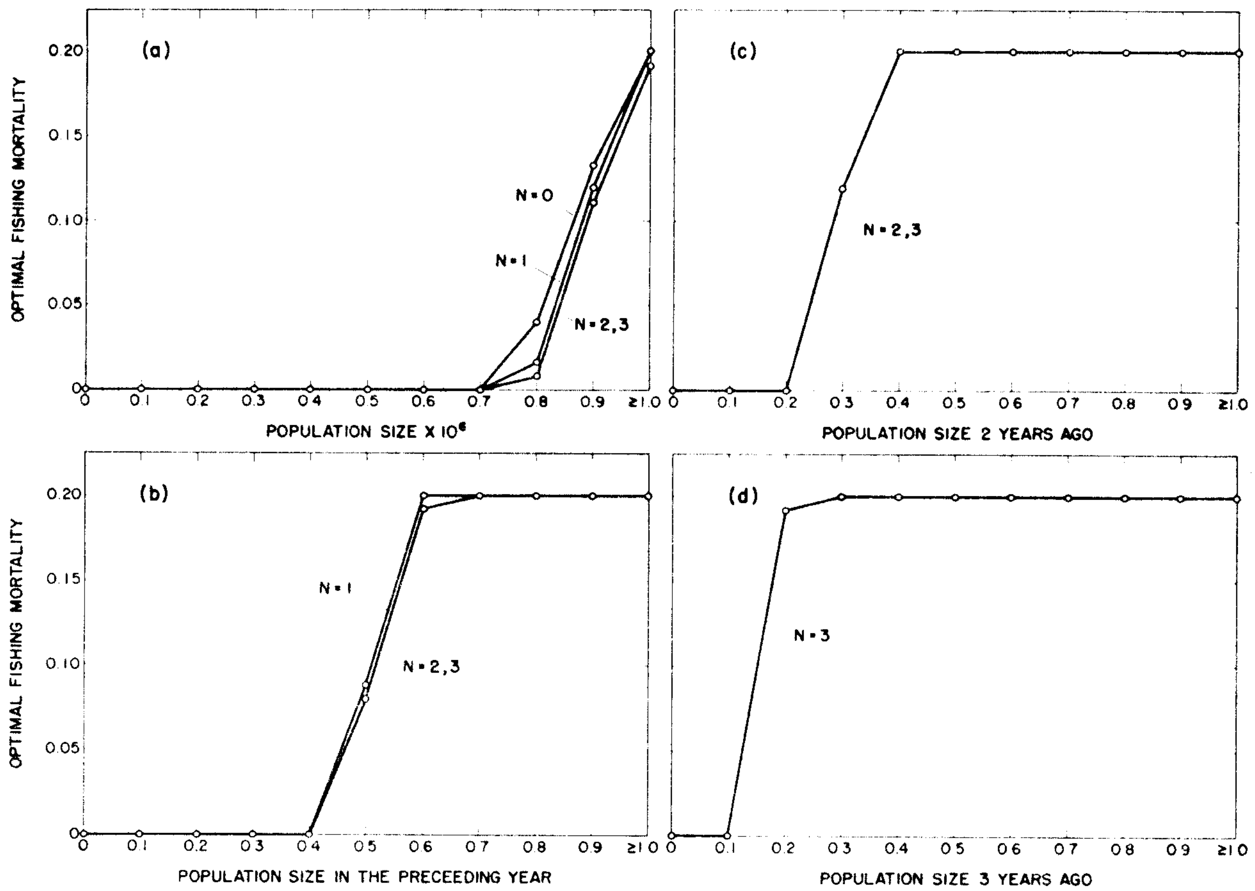
	Survey every year	One year between surveys	Two years between surveys	Three years between surveys
Survey every year	--			
One year between surveys	0.0*	--		
Two years between surveys	0.50482	0.50482	--	
Three years between surveys	0.7501	0.7501	0.2603	--

*The difference was less than the numerical accuracy of the computer program.

Maximum loss due to information delay = 7.31828.

Table 2. Maximum loss in total expected discounted harvest of salmon runs ($\times 10^6$).

Loss from delayed information	$\geq$ 26.234
Loss from 3 years without a survey	= 0.17882



(a)
(b)
(c)
(d)
OPTIMAL FISHING MORTALITY
0.20
0.15
0.10
0.05
0
N=0
N=1
N=2,3
N=3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
≥1.0
POPULATION SIZE X 10^6
POPULATION SIZE 2 YEARS AGO
POPULATION SIZE IN THE PRECEEDING YEAR
POPULATION SIZE 3 YEARS AGO

Figure 1

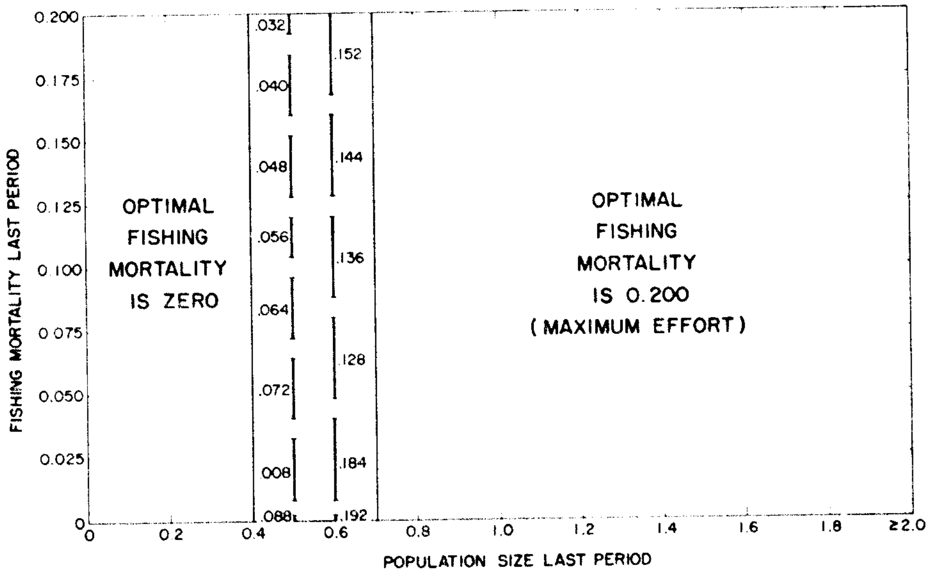
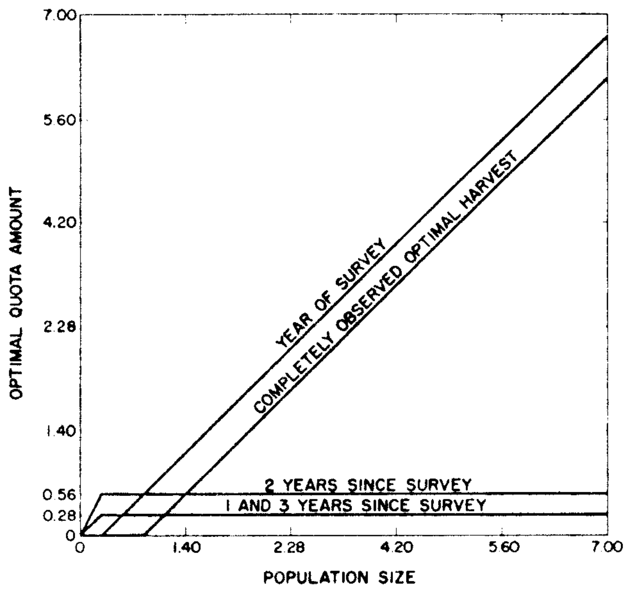

FISHING MORTALITY LAST PERIOD
POPULATION SIZE LAST PERIOD
OPTIMAL FISHING MORTALITY IS ZERO
OPTIMAL FISHING MORTALITY IS 0.200 (MAXIMUM EFFORT)
0.200
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
≥2.0
.032
.040
.048
.056
.064
.072
.008
.088
.152
.144
.136
.128
.184
.192

Figure 2



7.00
5.60
4.20
2.28
1.40
0.56
0.28
0
OPTIMAL QUOTA AMOUNT
YEAR OF SURVEY
COMPLETELY OBSERVED OPTIMAL HARVEST
2 YEARS SINCE SURVEY
1 AND 3 YEARS SINCE SURVEY
0
1.40
2.28
4.20
5.60
7.00
POPULATION SIZE

Figure 3